

SINGLE-PASS HARVEST OF CORN GRAIN AND STOVER: PERFORMANCE OF THREE HARVESTER CONFIGURATIONS

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ABSTRACT. Corn stover was harvested with a modified combine that simultaneously harvested grain and stover in separate streams. The harvester was used to collect the following stover fractions using three different heads: cob and husk (ear-snapper head); stalk and leaves (stalk-gathering head); and stalks, leaves, husk, and cob (whole-plant head). Cob and husk were also collected when using the stalk-gathering head, but in a separate stream from the stalks and leaves. Material harvested with the ear-snapper, whole-plant, or stalk-gathering head had average moisture of 38.2%, 45.0%, and 46.7% (w.b.); particle size of 14, 22, and 90 mm; and density in the transport container of 98, 64, and 40 kg DM m⁻³, respectively. Area productivity was 3.4, 1.5, and 1.9 ha h⁻¹; fraction of available stover DM actually harvested was 18%, 64%, and 49%; and total harvester specific fuel use was 1.46, 2.07, and 1.83 L Mg⁻¹ DM or 17.0, 33.4, and 27.4 L ha⁻¹ for the ear-snapper, whole-plant, and stalk-gathering head configurations, respectively. The untilled ground cover in the fall and spring was greater than the minimum requirement of 30% when using any of the three heads. Chisel plowing in the fall with twisted shovels buried too much residue no matter which harvester configuration was used. Chisel plowing in the spring with sweeps left sufficient residue when stover was harvested with either the ear-snapper or stalk-gathering heads. Material harvested with the ear-snapper, stalk-gathering, and whole-plant heads had an average density in a bag silo of 261, 111, and 160 kg DM m⁻³, respectively. Average loss in a bag silo was less than 4.3% of total stover DM after nine months of storage. Based on estimated cellulose and hemicellulose content, ethanol yield was 868, 1474, and 2804 L ha⁻¹ from materials harvested with the ear-snapper, stalk-gathering, and whole-plant heads, respectively.

Keywords. Biomass, Biomass harvest, Chemical composition, Corn stover, Density, Fuel use, Particle size, Power requirements, Storage.

Corn stover consists of all the above-ground, non-grain fractions of the plant including the stalk, leaf, cob, and husk. Corn stover has great potential as a biomass feedstock in North America, with potential annual yields of 130 Tg producing 38.4 GL of ethanol (Kim and Dale, 2004). The widespread adoption of corn stover as a biomass feedstock is limited by harvest challenges.

Corn stover is most often harvested as a dry product and packaged in large round or large square bales, typically involving as many as seven steps after grain harvesting (Shinnners et al., 2007a). Problems with this system include slow field drying, short harvesting window, frequent weather de-

lays, soil contamination, and low harvesting efficiency (ratio of harvested to total available stover mass). Harvesting efficiency ranged between 37% and 50% (Shinnners et al., 2007a). The many field operations resulted in high costs per unit harvested mass (Shinnners et al., 2003).

Harvesting wet stover immediately after grain harvest by combining shredding and windrow formation in one machine and then chopping with a forage harvester can eliminate the need for field drying and raking, and eliminate bale gathering, staging, and loading. Harvest efficiency with this method was 55% (Shinnners et al., 2007a). Ensiled storage of wet stover in a bag silo produced DM losses of less than 4%. Concerns with this harvesting method include forage harvester availability on grain farms, soil contamination, and high costs due to the number of field operations still required.

A single-pass harvesting system that produces corn grain and stover harvested in separate crop streams would further eliminate field operations and reduce costs. Previous research investigated single-pass harvesting in which the grain and non-grain fractions were separated, processed, and transported from the machine in separate streams (Albert and Stephens, 1969; Ayres and Buchele, 1971, 1976; Burgin, 1941; Buchele, 1976; Hitzhusen et al., 1970; Schroeder and Buchele, 1969). Shinnners et al. (2003) estimated that single-pass harvesting reduced total costs of stover delivered to a biorefinery by 26% compared to a dry bale stover option.

A single-pass harvester using either an ear-snapping or whole-plant corn head has recently been used to harvest various stover fractions (Shinnners et al., 2007b). The non-grain fractions were size-reduced with a flail chopper and then

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transported from the rear of the harvester by a blower. Harvesting efficiency ranged from 35% to 93% depending on the type of corn head and head height used. However, harvesting stover in this manner reduced area productivity by up to 50% (Shinners et al., 2007b).

An alternative single-pass system involves modifications to the combine head to size-reduce and transport the leaf and stalk fraction into a container pulled alongside header, reducing the volume of non-grain material through the harvester and potentially improving productivity. Virtually no modification to the combine harvester itself would be required, unless it was desired to also collect the husk and cob fractions from the rear of the harvester.

The objectives of this research were to modify a combine harvester to create two separate crop streams (grain and stover) using three harvester head configurations to capture different fractions of corn stover, to quantify the performance of the modified harvester and heads, and to quantify the storage characteristics of the harvested and ensiled stover.

MATERIALS AND METHODS

DESCRIPTION OF HARVESTER BASE UNIT

Modifications were made to a John Deere model 9750 STS combine so that single-pass, split-stream harvesting could be investigated (fig. 1). The first modification involved the addition of a flail chopper, cylindrical blower, and spout to the rear discharge of the combine to size-reduce and convey the non-grain fractions. The flail chopper rotor operated at 3200 rpm, was 1310 mm wide, with 30 pairs of hammers distributed on four rows. The hammers dragged material past 60 stationary knives, where size reduction took place. The theoretical length of cut (TLC, i.e., the spacing between the knives) was 22 mm. Material discharged from the chopper was expelled to a cylindrical blower mounted 1.4 m from the chopper. The 450 mm diameter blower was 510 mm wide,

had 12 paddles, and was belt driven at 1800 rpm. Material was discharged from the blower into a spout that concentrated the crop stream and directed the stream to a trailing wagon. The wagon was equipped with load cells to quantify harvested mass.

DESCRIPTION OF HARVESTER HEADS

Three different heads were used to harvest different stover fractions. First, a John Deere model 693 ear-snapper corn head was used without modification and served as the harvester control. In this configuration, the stover fractions targeted for collection were the cob, husk, and some leaf and upper stalk. Next, a John Deere model 666R whole-plant corn head normally intended for use with a forage harvester was adapted to the combine harvester to capture both the stover and grain fractions (Shinners et al., 2007b). All the standing stover fractions were targeted for harvest with this configuration.

The final head configuration involved a Slavutich model KMM-6 ear-snapper corn head (JSC Khersonsky Kombayny, Khereson, Ukraine) (fig. 2). The corn head was configured to not only snap the ears but to also gather and size-reduce the stalk and leaf. The corn head had a full-width knife rotor located below and behind the snapper rolls to gather and size-reduce stover before discharging it into an auger (fig. 3). In the second year of this test, the cross auger was modified to improve feeding by decreasing the inner diameter of the tube from 305 to 200 mm. The rotor had two knives, was 172 mm in diameter, and operated at 2270 rpm. The material gathered by the rotor and cross auger was fed into a cutterhead/blower, which further size-reduced the stover before discharging it to the spout, which directed the material into a wagon pulled alongside (fig. 4). The cutterhead/blower had four knives, was 600 mm diameter, and operated at 1588 (first year, 2005) or 2033 (second year, 2006) rpm. A single feed roll metered the material from the auger



Figure 1. Modified grain combine with whole-plant forage harvester corn head (photo courtesy of Wolfgang Hoffman).



Figure 2. Modified grain combine harvester with stalk-gathering head to gather, size-reduce, and transport the stalk and leaf fractions at the head.



Figure 3. Knife rotor used to gather and size-reduce the stover ejected from the snapping rolls of the stalk-gathering head.



Figure 4. Modified grain combine harvester with stalk-gathering head, collecting stalk and leaf in the front wagon and cob and husk in the rear wagon.

to the cutterhead. It was 320 mm diameter and operated at 298 (2005) or 200 (2006) rpm, so the TLC was either 25 (2005) or 44 (2006) mm. The cob, husk, and some leaf and upper stalk were also targeted for harvest when an additional wagon was used at the rear of the combine (fig. 4).

INSTRUMENTATION

Instrumentation to quantify machine performance was added in 2006. The shaft that drove the flail chopper and blower was instrumented with strain gauges and a slip ring assembly (model B6-3.2W, Michigan Scientific Corp., Charlevoix, Mich.) to measure shaft torque and speed. The clutch that operated the drive for the head and the feeder house was similarly instrumented to measure the torque and speed required by the head. All torque and speed signals were captured by a LabView data acquisition system at a frequency of 200 Hz. A fuel measurement system (model 8500, FloScan Instrument Co., Seattle, Wash.) was used to measure engine fuel use. It incorporated an opto-electronic turbine flow transducer with pulsation dampening elements in both the to-engine and leak-off fuel lines. Difference between these two

flows was total fuel consumed by the engine. The fuel flow-meter was zeroed at the beginning of each test, and a digital output to the nearest 0.1 L was hand recorded after each test.

FIELD TRIALS - 2005

A replicated block field experiment was conducted on 15 October (trial 1) and 10 and 11 November (trial 2) 2005 at the Arlington Agricultural Research Station (AARS) of the University of Wisconsin (UW) using a typical corn grain variety (table 1). Three head configurations were used: whole-plant, stalk-gathering, and ear-snapper. The three corn heads were set to operate at about 25, 30, and 55 cm above ground level, respectively. Maximum harvest height of the ear-snapper head was limited by the lowest height of the hanging ears. For each trial, nine separate plots of 250 m length by 4.6 m wide (6 rows) were used. Three replicate tests were conducted per treatment, and the three treatments and replicates were randomly assigned to the nine plots.

Ground speed was altered with the harvester hydrostatic transmission so that engine speed was maintained at about 2260 rpm in an attempt to maintain similar harvester loading

Table 1. Characteristics of crop used in quantifying the machine performance of the single-pass stover and grain harvester in 2005.

	Trial 1	Trial 2
Variety	Pioneer 34M93	Agri-Gold A6333 Bt
Comparative relative maturity (CRM) (day)	106	104
Planting date	18 Apr.	2 May
Harvest date	15 Oct.	10-11 Nov.
Ear height (mm)	1,210	1,245
Standing height (mm)	2,860	2,740
Plant population (plants ha ⁻¹)	67,040	70,600
Lodged	4.4%	NA
Pre-harvest loss (Mg DM ha ⁻¹)		
Leaf	0.13	0.37
Husk	--	0.02
Stalk	--	0.12

between treatments. Threshing cylinder and cleaning fan speed were 300 and 920 rpm, respectively. Time to harvest each plot was recorded so that ground speed and stover and grain mass flow rates could be calculated. Post-harvest stubble height was measured at 15 random locations in each plot. A wagon at the rear of the harvester collected stover, with an additional wagon pulled alongside to collect the stalk and leaf fractions when using the stalk-gathering head (fig. 4). Load cells on the wagons or grain cart were used to determine the mass of the stover or grain harvested from each plot to the nearest 2 kg. All measurements were taken with the wagon or cart stationary. The stover volume in the wagon was determined by leveling the loads and recording the material height. Three subsamples were collected per plot to determine moisture by oven drying the stover for 24 h at 103 °C and the grain for 72 h at 103 °C (ASABE Standards, 2007a, 2007c). Two stover subsamples per plot were collected for particle size analysis (ASABE Standards, 2007b).

Ground cover at fall tillage was quantified on 18 October 2005 (trial 1, table 1). The nine plots were split, and half of each plot was shredded with a stalk shredder at 10 cm height. A Glencoe model SS7400 seven-shank disk-chisel plow equipped with flat disks and 7.5 cm wide twisted shovels was then operated through the plots at 23 cm depth and 4 km h⁻¹. Ground cover at spring tillage was quantified on 15 April 2006 (trial 2, table 1). Plots were not shredded prior to tillage. The chisel plow was re-configured with 30 cm wide sweeps and then operated at 23 cm depth and 4 km h⁻¹. A line transect method (30 m string with markers at 30 cm spacing laid across the rows at a 45° diagonal) was used to quantify pre- and post-tillage ground cover in both the fall and spring (Al-Kaisi et al., 2003).

FIELD TRIALS - 2006

During the first four trials in 2006, the power and fuel consumption of the harvester as affected by the type of head was quantified (table 2). Each trial was considered a replicate, and four sub-replicate tests were conducted per trial. The heads were all operated about 50 cm above ground level. Maximum harvest height was limited by the lowest height of the hanging ears. The method of conducting the tests was the same as used in 2005. All other aspects of the machine setup were similar between the two years. The final two trials (table 2) quantified the effect of ground speed and mass flow rate on the machine performance when using the whole-plant and ear-snapper heads (trials 5 and 6, respectively). Ground speed was 4.5, 5.8, and 7.2 km h⁻¹ with the ear-snapper head and 2.4, 3.5, and 4.6 km h⁻¹ with the whole-plant head. Each ground speed level was replicated three times. The procedures for data collection were similar to those described above.

STORAGE

Stover from trial 2 in 2005 (table 1) and from trials 2 and 3 in 2006 (table 2) was stored in 3 m diameter plastic silo bags (one bag each year). Bags were made using a Kelly-Ryan (Blair, Neb.) 3 m diameter bagging machine. The bag diameter and length occupied by each load was measured to estimate density. The 2005 and 2006 silo bags were opened after 231 days (28 June 2006) and 273 days (8 August 2007), respectively. Four subsamples were taken at each load and oven dried at 65 °C for 72 h for moisture determination (ASABE Standards, 2007a). These samples were then hammer-milled to 1 mm particle size and analyzed for ash, crude protein (CP; Leco FP-2000A nitrogen analyzer), acid detergent fiber (ADF), neutral detergent fiber (NDF), and acid detergent insoluble lignin (ADL) using standard wet laboratory analysis techniques (Hintz et al., 1996). Cellulose and hemicellulose content were estimated by differences between ADF and ADL and between NDF and ADF, respectively. Two additional subsamples from each load location were collected, frozen, and analyzed for pH and common fermentation products (lactate, acetate, ethanol, and butyrate) using high-performance liquid chromatography (HPLC; Muck and Dickerson, 1988). Estimated ethanol yield after storage was predicted using the NREL theoretical ethanol yield calculator (USDOE, 2008) and assuming that the C6 sugars were the cellulose content multiplied by 0.86 and the C5 sugars were the hemicellulose content multiplied by 0.71 (Lorenz et al., 2009).

STATISTICAL ANALYSIS

Statistical analyses were done using single-factor analysis of variance or two-factor analysis when confounding effects (such as experiments conducted over several days) needed to be removed by blocking. The least significant difference (LSD) method was used to rank results (Steel et al., 1996).

Table 2. Characteristics of crop used in quantifying the machine performance of the single-pass stover and grain harvester in 2006.

	Trial 1 ^[a]	Trial 2 ^[a]	Trial 3 ^[a]	Trial 4 ^[a]	Trial 5 ^[b]	Trial 6 ^[b]
Variety (Pioneer brand)	35Y67	35Y67	35A30	34A16	34A16	34A16
Comparative relative maturity (CRM) (day)	105	105	103	108	108	108
Planting date	24 Apr.	24 Apr.	6 May	24 Apr.	24 Apr.	24 Apr.
Harvest date	28 Oct.	1 Nov.	17 Nov.	21 Nov.	8 Dec.	15 Dec.
Drooped ear height (mm)	950	935	900	800	935	900
Stover moisture (% w.b.)	45.8	40.7	36.8	32.9	31.6	30.9
Grain moisture (% w.b.)	25.6	21.5	21.0	20.9	20.1	20.0

^[a] Trials quantifying the effect of head type on combine performance using three head configurations.

^[b] Trials quantifying the effect of ground speed on combine performance using whole-plant head (trial 6) and ear-snapper head (trial 7).

RESULTS

MACHINE PERFORMANCE AS AFFECTED BY HEAD TYPE

Grain yield was about 10% less in 2006 than in 2005 (table 3), so it can be assumed that available stover yield was also 10% less in 2006 (Shinners and Binversie, 2007). In 2006, the whole-plant and stalk-gathering heads were operated about 30 cm higher than in 2005 to leave more material in the field for erosion protection and to preserve soil nutrients (Hoskinson et al., 2007). Stover yield on a DM basis from the whole-plant head was 16% less in 2006 than in 2005 (table 3). If stover yield was 10% less, then the additional 30 cm in head height produced a 6% drop in stover harvesting efficiency. Changes in head height did not affect year-to-year stover yields with the ear-snapper head or from the rear of the combine equipped with the stalk-gathering head. Yields of stalk and leaf from the stalk-gathering head were down only 11% from 2006 to 2005, despite operating the head considerably higher in 2006. This was attributed to improved material capture from the higher capacity auger used

in 2006. It was observed that there was improved collection of cut stalks when the high-capacity auger was used.

The trend for differences in moisture between the various fractions was similar in both years, although the range tended to narrow in 2006. Material was harvested later in 2006, and fractional moisture differences tend to narrow as the fall progresses (Shinners and Binversie, 2007). In addition, the higher harvest height used in 2006 would have left more of the high-moisture bottom stalk unharvested. Grain yield was slightly lower with the stalk-gathering head in 2005 due to ear loss. The higher height used with the stalk-gathering head in 2006 reduced the slope of the snapping rolls and reduced ear loss, so grain yield was similar for all heads used in 2006.

Area productivity with the ear-snapper head was twice that with the whole-plant head, similar to results found in 2004 (Shinners et al., 2007b). The stalk-gathering head had greater area productivity than the whole-plant head in both years (table 4). Ground speed was limited with both configurations by plugging at the size-reduction components rather than due to power limitations. With the stalk-gathering

Table 3. Stover and grain yield for the different head types based on mass of material harvested.

Head Type	Ratio of Head to Ear Height	Aggregate Stover Moisture (% w.b.)	Mass of Material Harvested (Mg ha ⁻¹)			
			Stover WM	Stover DM	Grain WM	Grain DM
2006 ^[a]						
Ear-snapper	0.57	36.9 a	2.9 a	1.8 a	13.0	10.1
Whole-plant	0.50	38.8 b	10.0 d	6.1 d	12.8	9.9
Stalk-gathering ^[b]	0.43	39.4 b	8.3 c	5.0 c	13.0	10.2
Front wagon		41.0 c	5.5 b	3.2 b		
Rear wagon		36.0 a	2.8 a	1.8 a		
LSD ^[c] (P = 0.05)		1.5	0.4	0.2	1.1	0.9
2005 ^[d]						
Ear-snapper	0.45	39.4 a	3.5 a	2.1 a	14.7	11.1 b
Whole-plant	0.22	51.1 b	14.9 d	7.3 d	14.5	11.1 b
Stalk-gathering ^[b]	0.22	48.0 b	10.1 c	5.2 c	13.7	10.4 a
Front wagon		52.1 c	7.5 b	3.6 b		
Rear wagon		38.5 a	2.7 a	1.7 a		
LSD ^[b] (P = 0.05)		4.2	0.8	0.4	0.8	0.6

[a] Data from trials 1 through 4 described in table 2.

[b] Data in this row represent the aggregate or sum of the material collected from both the front and rear wagons.

[c] Means followed by different letters in the same column within a year are significantly different at 95% confidence.

[d] Data from trial 1 and 2 described in table 1.

Table 4. Stover and grain mass flow rates for the different head types based on mass of material harvested.

Head Type	Ratio of Head to Ear Height	Area Productivity (ha h ⁻¹)	Mass Flow (Mg h ⁻¹)			
			Stover WM	Stover DM	Grain WM	Grain DM
2006 ^[a]						
Ear-snapper	0.57	2.9 c	8.4 b	5.3 b	37.6 c	29.2 c
Whole-plant	0.50	1.4 a	14.3 d	8.8 c	18.7 a	14.6 a
Stalk-gathering ^[b]	0.43	1.8 b	14.8 d	8.8 c	23.2 b	18.1 b
Front wagon			9.9 c	5.7 b		
Rear wagon			4.9 a	3.1 a		
LSD ^[c] (P = 0.05)		0.1	0.8	0.5	3.0	2.4
2005 ^[d]						
Ear-snapper	0.45	3.4 c	12.0 b	7.3 b	50.4 b	38.1 b
Whole-plant	0.22	1.5 a	24.9 d	12.2 d	24.2 a	18.4 a
Stalk-gathering	0.22	1.9 b	18.4 c	9.5 c	25.0 a	18.9 a
Front wagon			13.6 b	6.5 b		
Rear wagon			4.8 a	3.0 a		
LSD ^[c] (P = 0.05)		0.3	2.3	1.2	3.7	2.2

[a] Data from trials 1 through 4 described in table 2.

[b] Data in this row represent the sum of the material collected from both the front and rear wagons.

[c] Means followed by different letters in the same column within a year are significantly different at 95% confidence.

[d] Data from trials 1 and 2 described in table 1.

Table 5. Particle size and bulk density in the wagon of the harvested stover fractions.

	Head Type	Ratio of Head to Ear Height	Stover Particle Size ^[a]		Wagon Density (kg m ⁻³)	
			Mean (mm)	Fraction Long ^[b] (%)	WM	DM
2006 ^[c]	Ear-snapper	0.57	12 a	23 a	147 c	93 c
	Whole-plant	0.50	25 b	34 b	92 b	56 b
	Stalk-gathering	0.43				
	Front wagon		72 c	81 c	74 a	42 a
	Rear wagon		13 a	26 a	153 c	98 c
	LSD ^[d] (P = 0.05)		4	3	10	6
2005 ^[c]	Ear-snapper	0.45	15 a	36 a	172 b	106 c
	Whole-plant	0.22	18 a	45 b	147 b	72 b
	Stalk-gathering	0.22				
	Front wagon		107 b	89 c	81 a	38 a
	Rear wagon		14 a	31 a	159 b	97 c
	LSD ^[c] (P = 0.05)		12	5	19	9

^[a] TLC was 22 mm for material size-reduced by the flail chopper at the rear of the harvester.

TLC was 44 and 25 mm for the stalk-gathering head (front wagon only) in 2005 and 2006, respectively.

^[b] Fraction of sample residing on the top screen of the particle size separator (ASABE Standards, 2007b).

^[c] Data from trials 1 through 4 described in table 2.

^[d] Means followed by different letters in the same column within a year are significantly different at 95% confidence.

^[e] Data from trials 1 and 2 described in table 1.

Table 6. Fuel use and specific energy requirements for single-pass harvesting of corn grain and stover using three harvester heads (trials 1 through 4, table 2).

Head Type	Fuel Use			Mass Flow				Specific Energy			
	(L Mg ⁻¹) ^[a]		(L ha ⁻¹)	Wet (Mg WM h ⁻¹)		Dry (Mg DM h ⁻¹)		Wet (kWh Mg ⁻¹ WM)		Dry (kWh Mg ⁻¹ DM)	
	Wet	Dry		Head ^[a]	Rear ^[b]	Head ^[a]	Rear ^[b]	Head ^[a]	Rear ^[b]	Head ^[a]	Rear ^[b]
Ear-snapper	1.10 a	1.46 a	17.0 a	46.0 b	8.4 b	34.5 b	5.3 b	0.8 b	7.3 b	1.1 b	11.2 b
Whole-plant	1.36 c	2.07 c	33.4 c	33.0 a	14.3 c	23.4 a	8.8 c	0.4 a	5.1 a	0.5 a	7.8 a
Stalk-gathering	1.30 b	1.83 b	27.4 b	36.0 a	4.9 a	25.7 a	3.1 a	2.0 c	9.8 c	2.7 c	15.0 c
LSD ^[c] (P = 0.05)	0.03	0.17	1.3	3.8	0.9	2.9	0.6	0.2	0.8	0.4	1.2

^[a] Mass of both grain and stover fractions harvested with corn head.

^[b] Mass of stover harvested from rear of harvester.

^[c] Mean values followed by different letters in the same column are significantly different at 95% confidence.

head, material plugged the spout at high feed rates, as large particles wedged in the neck of the spout.

The TLC of the flail chopper was 22 mm. The measured particle size was near or below the TLC when the ear-snapper or whole-plant head was used (table 5). This was an unexpected result because the actual particle size of forages is almost always greater than the TLC on a forage harvester (Shinners, 2003). The fact that measured particle size was smaller than the TLC probably was due to material recirculation in the flail chopper. Measured particle size of material harvested with the stalk-gathering head was considerably less in 2006 than in 2005 because the TLC was reduced from 44 to 25 mm. However, in both years, the actual particle size was much greater than the TLC due to poor alignment of the material as it entered the cutting cylinder. In addition, the single feed roll was not able to sufficiently grip the material to prevent the cutterhead from pulling material from the nip, which also contributed to the long particle size. The density in the wagon was related to particle size and the fraction of crop harvested. The ear-snapper material had the highest wagon density because it had the smallest particle size and contained mainly cob, which has the highest particle density of the stover fractions (Savoie et al., 2004).

Even though total mass flow into the harvester (grain plus stover) was less with the whole-plant head, specific fuel consumption on per unit mass and per unit area basis was 42% and

96% greater, respectively, than with the ear-snapper head (table 6). The differences indicate the added energy required to process the additional material other than grain (MOG) through the threshing mechanisms and size-reduce it with the flail chopper. The harvester with the stalk-gathering head processed slightly greater total mass flow than with the whole-plant head, but specific fuel consumption on per unit mass and area basis was 12% and 18% less, respectively, than with the whole-plant head. These differences suggest the benefit that could be achieved by not passing the stalk fraction through the combine threshing mechanisms and by using a precision-cut cutterhead rather than flail chopper for size reduction.

The power required by the head and feederhouse was approximately 16%, 51%, and 92% of the maximum available (as determined by the belt drive capability) for the whole-plant, ear-snapper, and stalk-gathering heads, respectively. The power required by the flail chopper and blower at the rear of the combine was approximately 69%, 59%, and 46% of the maximum available for the whole-plant, ear-snapper, and stalk-gathering heads, respectively. Throughput was limited by material re-circulation and plugging constraints rather than by power, since less than 70% of the available power was used at the rear of the harvester. No matter which head was used, it was observed that material re-circulated in the flail chopper before it exited to the blower. Higher mass flow rates from faster ground speeds would

Table 7. Fuel use and specific energy requirements for single-pass harvesting of corn grain and stover using two types of harvester heads at various ground speeds (trials 6 and 7, table 2).

Speed (km h ⁻¹)	Fuel Use			Mass Flow				Specific Energy			
	(L Mg ⁻¹) ^[a]		(L ha ⁻¹)	Wet (Mg WM h ⁻¹)		Dry (Mg DM h ⁻¹)		Wet (kWh Mg ⁻¹ WM)		Dry (kWh Mg ⁻¹ DM)	
	Wet	Dry		Head ^[a]	Rear ^[b]	Head ^[a]	Rear ^[b]	Head ^[a]	Rear ^[b]	Head ^[a]	Rear ^[b]
Ear-snapper head ^[c]											
4.5	1.17	1.50	20.4	39.2	5.6	30.7	3.8	2.1	10.3	2.7	14.9
5.8	0.93	1.18	16.2	51.5	7.4	40.4	5.1	1.7	9.0	2.2	13.0
7.2	0.86	1.10	14.9	62.8	9.1	49.2	6.3	1.5	8.3	2.0	12.0
Whole-plant head ^[c]											
2.4	1.47	1.93	34.3	25.7	9.6	19.5	6.7	0.7	6.2	0.9	8.8
3.5	1.13	1.50	27.0	38.2	14.6	28.8	9.9	0.5	5.5	0.6	8.1
4.6	1.03	1.38	24.7	49.8	19.2	37.4	12.9	0.4	5.2	0.6	7.7

[a] Mass of both grain and stover fractions harvested with the corn head.

[b] Mass of stover harvested from rear of harvester.

[c] Stover moisture was 30.9% and 31.6% (w.b.) for the ear-snapper and whole-plant heads, respectively.

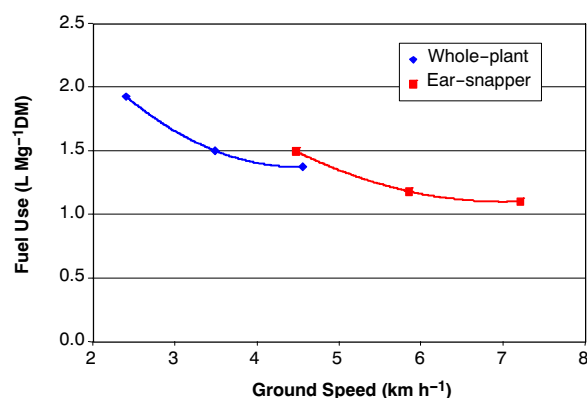


Figure 5. Fuel consumption per unit mass of grain plus stover as a function of ground speed for the whole-plant and ear-snapper heads (trials 5 and 6, table 2).

eventually cause so much material re-circulation that plugging occurred at the entrance to the flail chopper.

MACHINE PERFORMANCE AS AFFECTED BY GROUND SPEED

Specific fuel consumption was measured over a range of ground speeds (table 7, figs. 5 and 6). At low mass flow rates, the no-load fuel requirements made up a significant fraction of the total. The harvester approached equilibrium conditions at about 3.5 and 6.0 km h⁻¹ when using the whole-plant or ear-snapper heads, respectively. At equilibrium, the total dry mass flow rate of grain and stover was 32% greater when using the ear-snapper head, but specific fuel consumption was 40% less on a per unit area basis and 20% less on a per unit mass basis (table 7). At approximately 40 Mg DM h⁻¹ throughput, grain made up 66% and 87% of the total DM for the whole-plant and ear-snapper heads, respectively. At this throughput, the specific fuel use per unit mass and per unit area was 17% and 52% greater, respectively, when using the whole-plant head, showing that processing the extra stover brought in by the whole-plant head was more power intensive than threshing and separating grain when using the ear-snapper head.

RESIDUE COVER

It is recommended that 30% residue cover at the time of planting is the minimum required for adequate protection from excess soil erosion, although this value will vary depending on soil type, topography, and local climate (USDA-NRCS, 2003).

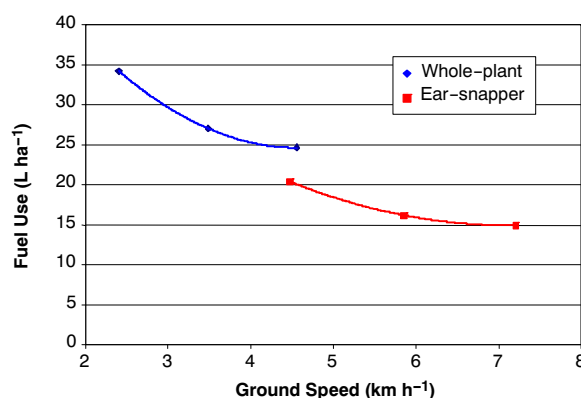


Figure 6. Fuel consumption per unit area as a function of ground speed for the whole-plant and ear-snapper heads (trials 5 and 6, table 2).

Any of the harvester configurations would have provided this minimum residue cover prior to fall or spring tillage (table 8). In the fall, the tillage tool was equipped with twisted shovels, so it aggressively turned under the residue so that none of the treatments would have provided adequate cover after tillage. In the spring, when the disk-chisel plow was equipped with sweeps, only the use of the whole-plant head would have left insufficient residue after tillage.

STORAGE

It was not possible to distinguish individual loads when the contents of the silos were removed, so there were no replicates available to conduct a statistical analysis of DM loss. The DM loss based on difference in total dry mass into and out of the silos was 4.1% and 4.4% of total DM in 2005 and 2006, respectively. The small moisture content differences between into and out of storage support these levels of DM loss (tables 9 and 10). Changes in ADF and NDF concentration during storage were small and likely due to DM loss and sampling or analysis error. Ash content was less for the ear-snapper material because this material included very little stalk, which might have been subjected to rainfall splash of soil. Material harvested with the ear-snapper head was lower in CP and higher in NDF and hemicellulose than the material harvested with the other two heads because it consisted mainly of cob and husk. There was no difference in cellulose content between materials. The pH was higher and concentrations of fermentation products were lower in 2006 because of

Table 8. Ground cover (%) determined by using transect method both before and after fall and spring tillage using a disk-chisel plow with twisted shovels (fall) and sweeps (spring).

	Head Type	Pre-Tillage Residue Mass (Mg DM ha ⁻¹)	Pre-Tillage		Post-Tillage	
			As Harvested	Shredded	As Harvested	Shredded
Fall 2005	Ear-snapper	6.7	91 c	96 c	25 b	19 b
	Whole-plant	1.1	39 a	55 a	7 a	9 a
	Stalk-gathering	3.2	78 b	86 b	12 a	13 ab
	LSD ^[a] (P = 0.05)		7	11	8	6
Spring 2006	Ear-snapper	9.8	98 c		56 b	
	Whole-plant	1.9	50 a		22 a	
	Stalk-gathering	4.2	73 b		35 a	
	LSD ^[a] (P = 0.05)		2		8	

^[a] Means with different markers in the same column within a year are significantly different at 95% confidence.

Table 9. Chemical composition as determined by wet lab analysis for stover stored in a bag silo from 10 November 2005 to 31 June 2006.

	Head Type	Moisture (% w.b.)	Chemical Components (% of total DM)						
			CP	ADF	NDF	ADL	Ash	Cellu- lose ^[a]	Hemi- cellulose ^[b]
Into Storage	Ear-snapper	38.1 a	3.8 a	41.2 a	79.6 c	1.3 a	3.5 a	39.9	38.5 b
	Whole-plant	50.5 b	5.0 b	41.3 a	72.4 a	2.4 b	5.5 b	38.9	31.1 a
	Stalk-gathering ^[c]	51.6 b	5.6 c	42.7 b	74.5 b	2.7 b	5.2 b	40.1	31.8 a
	LSD ^[d] (P = 0.05)	4.2	0.4	1.1	1.9	0.5	0.5	1.3	1.3
Out of Storage	Ear-snapper	42.3 a	4.6 a	41.5	80.3 c	1.8 a	2.7 a	39.7	38.8 b
	Whole-plant	51.5 b	5.2 b	42.0	72.7 b	2.6 b	4.5 b	39.4	30.7 a
	Stalk-gathering ^[c]	52.7 b	5.8 c	41.0	70.7 a	2.5 b	4.7 b	38.4	29.7 a
	LSD ^[d] (P = 0.05)	3.4	0.4	1.2	1.2	0.4	0.9	1.3	1.2

^[a] Cellulose estimated by difference between ADF and ADL.

^[b] Hemicellulose estimated by difference between NDF and ADF.

^[c] Material from the front wagon only, consisting of mainly stalk, leaves, and some husk.

^[d] Means followed by different letters in the same column are significantly different at 95% confidence.

Table 10. Chemical composition as determined by wet lab analysis of stover stored in a bag silo from 8 November 2006 to 8 August 2007.

	Head Type	Moisture (% w.b.)	Chemical Components (% of total DM)						
			CP	ADF	NDF	ADL	Ash	Cellu- lose ^[a]	Hemi- cellulose ^[b]
Into Storage	Ear-snapper	34.0	3.2	46.3	86.0 c	2.9	1.9 a	43.4	39.8
	Whole-plant	36.5	3.7	45.8	79.4 b	2.6	3.2 b	43.2	33.6
	Stalk-gathering ^[c]	34.9	3.9	46.0	77.0 a	2.6	4.8 c	43.5	31.0
	LSD ^[d] (P = 0.05)	3.6	0.7	2.3	1.6	0.7	0.7	2.6	1.7
Out of Storage	Ear-snapper	34.1 a	3.3 a	44.6	83.1 b	2.7 ab	2.5 a	42.0	38.4
	Whole-plant	37.9 b	4.2 b	44.3	78.6 a	2.5 a	3.3 b	41.8	34.2
	Stalk-gathering ^[c]	35.7 ab	4.5 b	44.6	78.1 a	3.0 b	3.6 b	41.6	33.5
	LSD ^[d] (P = 0.05)	2.5	0.4	2.5	3.8	0.4	0.7	2.5	2.2

^[a] Cellulose estimated by difference between ADF and ADL.

^[b] Hemicellulose estimated by difference between NDF and ADF.

^[c] Material from the front wagon only, consisting of mainly stalk, leaves, and some husk.

^[d] Means followed by different letters in the same column are significantly different at 95% confidence.

Table 11. Storage density, fermentation products, and estimated ethanol yield for ensiled stover stored in a bag silo.

	Head Type	Moisture (% w.b.)	Silo Density (kg DM m ⁻³)	pH	Lactate (% of total DM)	Acetate (% of total DM)	Ethanol (% of total DM)	Estimated Ethanol Yield ^[a]	
								(L Mg ⁻¹ DM)	(L ha ⁻¹)
2006	Ear-snapper	34.1 a	234	4.5	0.7	0.5 a	0.3	462	790
	Whole-plant	37.9 b	128	4.5	1.2	1.0 b	0.2	439	2647
	Stalk-gathering ^[b]	35.7 ab	102	4.7	1.1	0.8 ab	0.1	434	1528
	LSD ^[c] (P = 0.05)	2.5		0.3	0.8	0.4	0.3		
2005	Ear-snapper	42.3 a	288	4.3	0.9 a	0.8 a	0.6 b	450	946
	Whole-plant	51.5 b	192	4.2	3.6 b	1.5 b	0.2 a	405	2961
	Stalk-gathering ^[b]	52.7 b	120	4.2	3.9 b	1.7 b	0.3 a	394	1420
	LSD ^[c] (P = 0.05)	4.2		0.1	0.9	0.4	0.1		

^[a] Estimated ethanol yield using NREL theoretical ethanol calculator (USDOE, 2008) and cellulose and hemicellulose estimates from tables 9 and 10.

^[b] Material from the front wagon only, consisting of mainly stalk, leaves, and some husk.

^[c] Means followed by different letters in the same column within a year are significantly different at 95% confidence.

the lower moisture than in 2005 (table 11). There was virtually no butyric acid found in any of the samples in both years (data not shown), indicating no clostridia fermentation took place. Density in the silo bag was lower across all materials in 2006 because initial moisture was lower and the dry material was more resistant to compacting forces (table 11). Differences in density between materials harvested with the different heads were related to differences in particle size and the fraction of stover harvested by each head (table 5). Estimated ethanol yield per unit mass was 9% greater for the material harvested with the ear-snapper head because this material had higher estimated hemicellulose content. However, the overall DM yield was low when using this head, so ethanol yield per unit area with the ear-snapper head was 31% and 58% of that using the stalk-gathering and whole-plant heads, respectively.

SUMMARY

Corn stover was harvested with a modified grain combine harvester that simultaneously harvested grain and stover in separate streams. The harvester was used to collect the following stover fractions using three different heads: cob and husk (ear-snapper head); stalk and leaves (stalk-gathering head); and stalks, leaves, husk, and cob (whole-plant head). Cob and husk were also collected from the rear of the harvester when using the stalk-gathering head, but in a separate stream. Stover harvested with the ear-snapper head had the lowest moisture, smallest particle size, greatest bulk density, but lowest yield. Stover yield was more than three times greater when using the whole-plant head, but area productivity was 44% less and fuel use per unit area was 92% greater. The stover yield was 23% less with the stalk-gathering head compared to the whole-plant head, and the material it harvested was unacceptably long and low in bulk density. Using any of the three heads left sufficient residue for erosion protection if no fall tillage was done, but chisel plowing with twisted shovels buried too much residue no matter which harvester configuration was used. Cob and husk had 63% greater density in a bag silo than whole-plant stover. Levels of fermentation products after nine months of storage were substantially lower than in conventional whole-plant corn silage but were nevertheless sufficient to result in very small DM losses (<4.3%). On a per unit mass basis, post-storage cob and husk had an 8% greater theoretical ethanol yield than whole-plant stover due its higher estimated hemicellulose content, but its ethanol yield on a per unit area basis was 69% less due to low DM yield.

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NOMENCLATURE

ADF = acid detergent fiber
ADL = acid detergent insoluble lignin
CP = crude protein
CRM = comparative relative maturity
DM = dry matter
LSD = least significant difference
MOG = material other than grain
NDF = neutral detergent fiber
P = probability
TLC = theoretical length of cut
WM = wet matter